Hybrid Composites for Morphing Applications

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ABSTRACT

. This work is directed towards realizing large scale shape changes of wing like structures. It is relevant to discuss the work carried out in this area so far. AMR BAZ (ref.1) details the work in which SMA is embedded in sleeves located at the neutral planes and arranged parallel to the longitudinal axis of the composite beam. Here emphasis is placed on describing quasi-static theory of shape control and implementation of this theory to composites incorporated with SMA. Emphasis has been placed on full utilization of shape memory effect without compromising on structural stiffness of the composite beam. Koryo Miura et al (ref.2) explain about adaptive structures and their use in aerospace applications. Here a variable geometry (VG) truss concept is presented. Comparison is made between tetrahedral and octahedral truss elements. Since octahedral is richer in symmetry, it is considered to be adequate for adaptive structures. DC motor is used as an actuator. It is shown that VG truss is the basic form of adaptive structures. The basic formulations for its geometrical as well as vibrational properties are established. Some applications such as second generation manipulator arm, support architecture for a space station and others are discussed here.

Deepak.S.Ramrakhyani et al (ref.3) explains about the use of compliant cellular truss where tendons are used as active elements. This tendon actuated elements can be used for local or global shape changes. Here an octahedral unit cell is developed for bending deformations and compliant joints are made of cylindrical elements of superelastic shape memory alloys. Several concepts of morphing skin were also presented. Tendon actuators are presently under development. The tendons could be actuated locally or combined from a remote location such as the root of the wing.

Since we are looking for large deflection of thin beams we have deliberately embedded the SMA wires off the neutral axis of the beam. In the literatures there is hardly any material that deals with this type of an approach. In this the effect of embedding the thermal SMA wires off the neutral plane of thin beams was studied. These wires were prestrained and embedded off the neutral axis to produce high amount of recovery forces when electrically energized. Superelastic SMA (SE SMA) wires were used on the other side of the beam so as to increase the spring back effect of the beam when de-energized. Thus we were able to obtain large deflection together with faster return back to original position when de-energized.

Keywords: SMA, SE SMA, SIM, martensite, austenite etc.

2. DETERMINATION OF PROPERTIES OF SMA ACTUATOR

Shape memory effects in SMA are classified as (a) Temperature induced and (b) Stress induced.

(a) Temperature Induced: Here if the material is deformed in martensite it remains in the same condition until heated. When it is heated it transforms back in to the original austenite (parent) thereby regaining the original shape. This is called thermally induced shape memory effect.

(b) Stress Induced: Stress induced SME occurs when the material is in its austenite phase. Stress induced martensite (SIM) is realized when the material is loaded in the austenite condition up to a certain load. On removal of the load the SIM transforms back to the more stable austenite. This stress induced behavior of SMA is called as superelasticity.

Shape memory devices can act without constraint to freely recover their trained shape, or can be fully constrained so that they provide a force or can be partially constrained so that they perform work. Recovery stress generated in fully constrained position is shown in fig.1. For the chosen SMA wire the transformation temperatures are as follows. $M_f = 25^0$C, $Ms = 34^0$C, $A_s = 55^0$C & $A_f = 80^0$C. The recovery stress generation for the sequence can be explained as follows. The material in the martensite condition is strained from point O up to point A and then fixed at both ends. It is then heated from martensite to austenite along the path AB. At B the material is in austenite condition. Here the path AB is parallel to the stress-temperature plane of the figure. The difference between stress at point A and point B gives the recovery stress.

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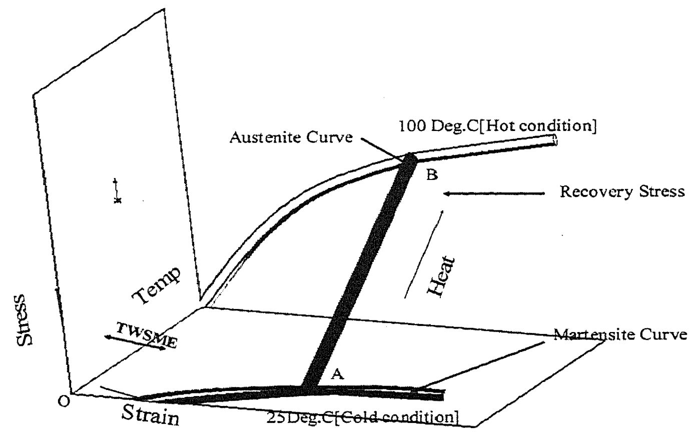


Fig.1. Recovery Stress Generation in Fully Constrained Condition

Before embedding in the beam, various tests were conducted to determine the properties of SMA actuator element.

2.1 Stress-Strain Test of SMA in Martensite and Austenite Condition

The thermal SMA wire of 1.2mm dia. which was heat treated (soaking at 450^{0}C for half an hour, and quenching in water) was loaded up to failure in the Tinius Olsen tensile testing machine at room temperature (martensite condition) and at a temperature of 120^{0}C(austenite condition). In martensite condition there is an appearance of distinct plateau region in stress-strain graph. A plateau region is also present in the austenite condition as shown in fig.2(a). The plateau region was absent in either of the cases (i.e. in both martensite and austenite condition) in the case of trained wires as shown in fig.2 (b). The trained wire also exhibited a two way shape memory.

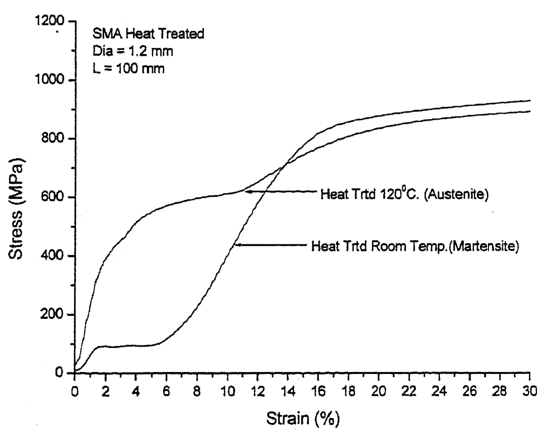


Fig.2 (a). Stress Vs Strain Curve for Heat-Treated Wire

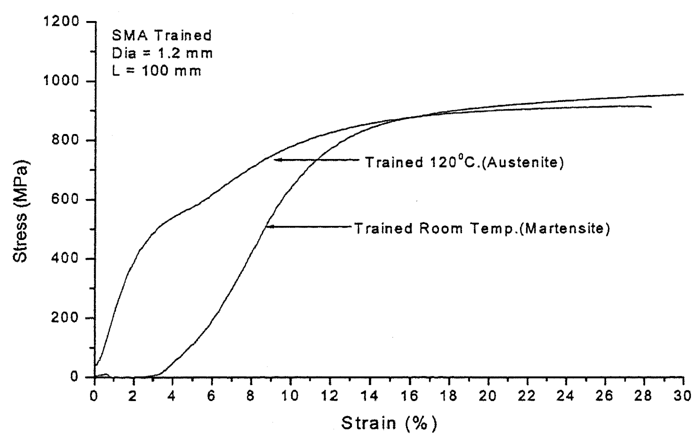


Fig.2 (b). Stress Vs Strain Curve for Trained Wire

2.2 Thermomechanical Training of SMA Elements

Thermomechanical training was done to stabilize the property and to obtain consistent and repeatable properties. This is done using a test set up shown in fig.3. Here the thermal SMA wire of 1.2mm dia. was loaded up to 34Kg for a stress corresponding to 300Mpa and was heated by a current of 5A for 30Sec and cooled for 60Sec. This process was repeated until stabilized values of max: load and min: loads were observed. The stress value corresponding to maximum load and mi9mimum load are 500MPa and 100Mpa respectively.

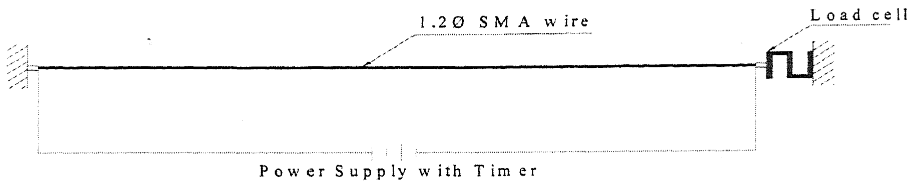


Fig.3. Set-up for SMA training

Details of the training set-up:
Material of the wire – NiTiCu, Diameter of the wire – 1.2mm, Length of the wire – 2500mm
On time – 30s, Off time – 60s, Ambient temperature – 29^0C, Preload on the wire – 34.6kg
Current – 5A, voltage – 14V
Calculation of total time taken for training
Total no of cycles – 200
Time taken for 1 cycle – (30+60) – 90 Sec
Total time taken – 200 X 90 – 18000Sec – 5 hrs
The trained wire are cut in to 3 pieces each of length 600mm and used in beam fabrication.
The variation of the stress with no. cycles are shown in the fig.4

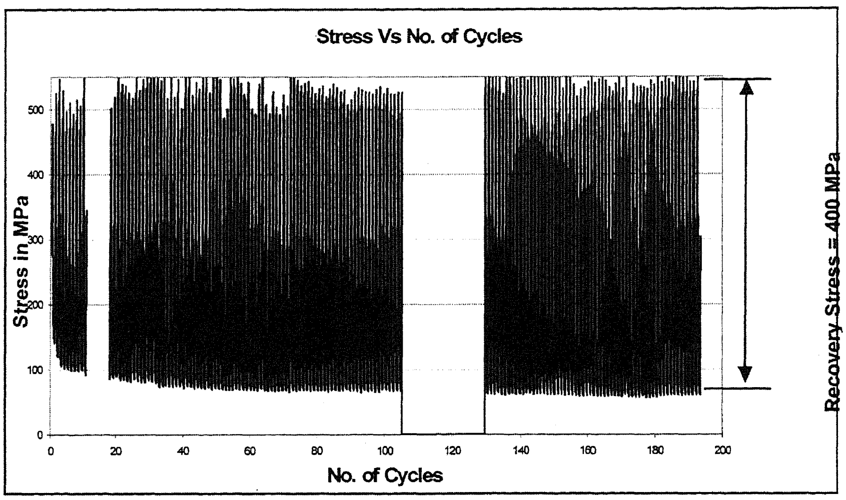


Fig.4. Stress Vs No of cycles

2.3 Evaluation of Recovery Stress in SMA Element when it is Electrically Energized

Recovery stress is the stress generated when the SMA element undergoes transformation from martensite to austenite. This value is obtained from the training data where the SMA element is fixed between two supports and heated and cooled cyclically to undergo martensite to austenite and austenite to martensite transformation. The maximum value of this stress in a fully constrained condition can be as large as 400Mpa. This value is taken from fig.4.

3. FABRICATION OF SMA EMBEDDED COMPOSITE BEAM

Two different types of beams were fabricated. One is flat beam (beam1) and other is a curved beam (beam2). This is to verify that it is possible to obtain flat to curved as well as curved to flat upon actuation of the beams.

3.1 SMA Embedded Composite Beam1

3.1.1 Design and Development of Jig to Pre-Strain the SMA Element

Jig was designed and fabricated to pre-strain the SMA wire element before embedding in the FRP beam. To obtain maximum recovery force it is necessary to pre-strain the wire by a net amount of 2.5% before embedding (i.e. the wires are strained by 3% and later relieved by 0.5%). This will maximize the amount of recovery force which the SMA element can generate while it is activated. The photograph of the jig used for pre-straining the SMA is shown in fig.5

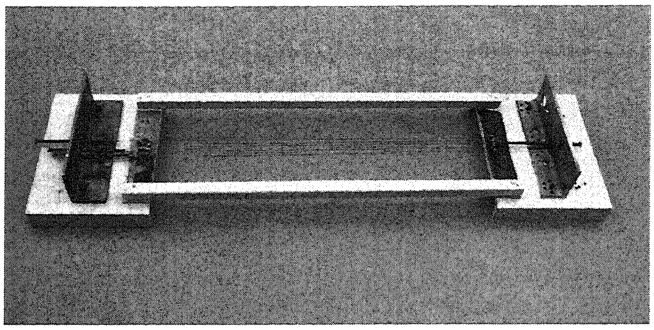


Fig.5 Jig for pre-straining SMA wire

A combination of jig developed to pre-strain the SMA element and a surface plate where the GFRP beam is placed is used for fabrication of GFRP beam. Here layers are built up on the surface plate for the required thickness (~ 1mm) of beam and later the pre-strained wires (on the jig) are kept above the lay-up just touching it.

3.1.2 Bonding the Thermal SMA wire to the Composite Beam

This bonding of SMA to the beam was done in three stages as follows

3.1.2.1 STAGE- 1

The required thickness (1 mm) of the beam was built using the plain wave bi-directional glass fabric of 0.125mm thickness and resin mixture. The resin system used was LY5210 with hardner of HY932 and accelerator of DY219 in the ratio 100:56:1. The length and width of the beam was kept as 410mm and 45mm respectively. This lay-up is then longitudinally slitted in to three pieces of width 15mm each and is kept symmetrically below the three pre-strained SMA wires. The SMA wires that are strained by 3% and released by 0.5% in the jig were crimped by Cu sleeves to avoid the relative motion between SMA and beam. Over these SMA wire glass fabric strips of 25mm width and length equal to width of the beam (45mm) are cut and placed with 5mm spacing.

The lay-up is then covered by porous release film and breather cloth and this whole set-up was packed using vacuum bag. The vacuum value is carefully inserted in a corner, which was connected to vacuum pump. It was kept under vacuum for 24 hours for curing. During the entire process of curing the SMA wires are kept in a pre-strained condition.

3.1.2.2 STAGE-2

Since curvature was present after first stage of fabrication and inorder to get fully flat beam we have put super elastic SMA (SE SMA) wires exactly opposite to that of thermal SMA on the other side of the beam. To position the SE SMA wire on the other side of the beam we have used copper sleeves at the end of beam. The copper sleeves are fixed on to the beam by GFRP strip of 12mm$\times$45mm. To avoid flow of resin into the copper sleeves, which resist free movement of SE SMA in the sleeve we have put wax in to the sleeves.

The three heat treated (heated at 500^{0}C for 15 minutes and immediately quenched in water) SE SMA wires of 0.6mm dia. were passed in to the sleeves and fixed on to the jig. SE SMA wires are strained up to 3% and released by 0.5%. After straining of wire the beam became flat. To lock SE SMA wire in this condition we have cut GFRP strip of 25$\times$45 mm and 1mm thick (8 layers of 5mill fabric). These intermittent strips are placed throughout the length of the beam with a 5mm space between strips. Then beam is kept for curing in vacuum for 24 hours.

3.1.2.3 STAGE-3

After curing the beam was not perfectly flat. However but it gave good results while actuating. But the aim of our project was to get perfectly flat beams so we have planned to put one SE SMA wire of 1.2mm dia at the center of the beam. To position the wire at the center we again used the sleeves as that of previous stage. This time we have used different boundary condition i.e., the beam was fixed at one end and it was freely floating at the other end. One end of the SE SMA wire is fixed at one end of the beam, the other end is passed on to a freely moving frictionless pulley, which is carrying weight hanger. We have strained the wire by loading weight on the weight hanger up to 18kgs until the beam becomes perfectly flat.

To lock the position of wire at this condition on to the beam we have put continuous strip of 25$\times$410mm of 1mm thickness. Instead of conventional curing (curing by vacuum) this time we have cured GFRP strips held with help of crocodile clips for 24 hours. After removing from curing the beam was perfectly flat. The exploded view of the beam is shown in fig.6.

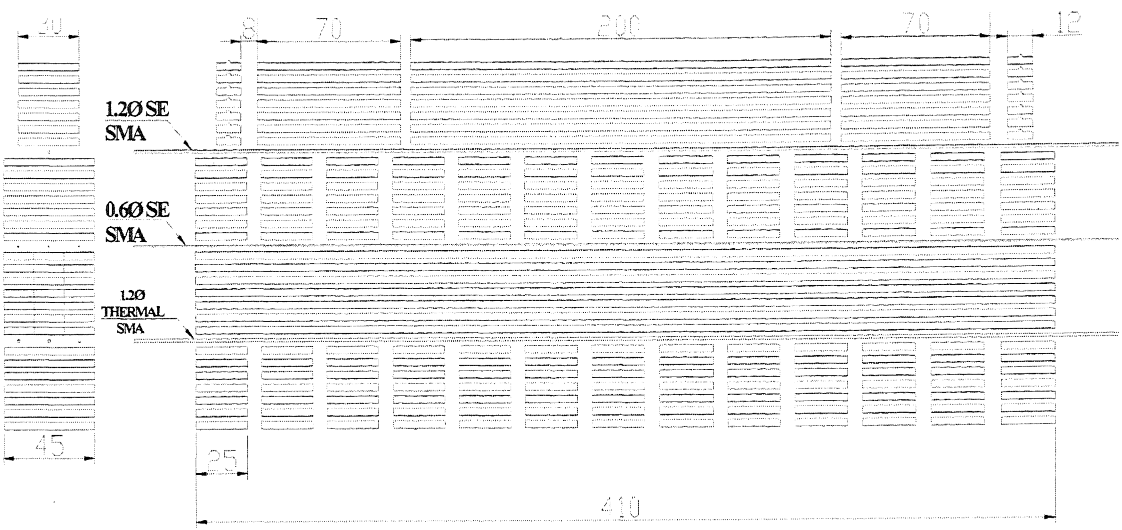


Fig. 6. Exploded View of the Beam

3.2 SMA Embedded Composite Beam2

Here we have decided to use only thermal SMA and get flat beam after bonding. For this curved beam was fabricated to start with. This curved beam was obtained by placing lay-up of GFRP fabrics (wetted with resin) on a curved tool surface. The curved tool was made of polyurethane foam where the top surface of the tool was in the form of an arc, and the deflection at center was set to be 60mm.

Over this the lay-up was done using 5mil glass fabric and resin. Seven layers were laid one over the other and were transferred on to the tool. This was then vacuum bagged and kept for 24hrs for curing. After removing from vacuum it was found that the beam was curved.

It was later decided to place 0.5mmdia trained thermal SMA wires (3nos) over the lay up as a second stage curing. For this on the top surface of the beam six sleeves were positioned with three on one end and three on other end. Through these sleeves 3 thermal SMA wires were passed and later the wire was strained on a jig so that the beam became flat. Now intermittent strip were used to bond thermal SMA to the beam. It was vacuum bagged and kept for 24hrs for curing. After removing from the bag the beam was found to have slight curvature. The beam construction was similar to the previous beam except that there was no SE SMA wires used.

4. TESTING OF SMA EMBEDDED COMPOSITE BEAMS

The beam was tested by heating (ON TIME) using a current of 5.5 Amps. per wire for beam1 and 1.5 Amps. per wire for beam2. Experiments for load bearing capacity, deflection and repeatability were done for the boundary condition shown in fig.7

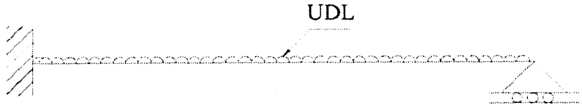


Fig.7. Schematic test set-up of beam

4.1 Simulated Aerodynamic loading

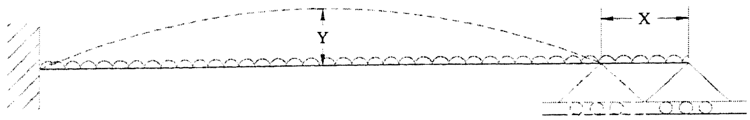
The beam was tested under simulated aerodynamic loading for deflection. Sand bags (each weighing 50gm) were placed over the beam so as to produce a net load of 0.5kg. The UDL of the above load is 1.22kg/m and pressure is 27.1kg/m^2.

The response time for all the beams are 120 sec (2 min) and cooling time 600 sec (10 min). The results are tabulated as follows.

4.1.1 Tabulation of Test Result

4.1.1a Beam1

Loading condition: UDL of 0.5 kg, Boundary condition: One end fixed and other end sliding
Length of Beam: 410mm, Width of beam: 45mm, Dia of Thermal SMA: 1.2mm
, Dia of SE SMA: 0.6mm (2nd stage) and 1.2mm (3rd stage)



Sl. No.	Current (Amp)	Deflection Y (mm)	Heating Time (sec)	Cooling Time (sec)	Remarks
1	16.5	4.5	120	600	Came back to original position
2	16.5	5	120	600	"
3	16.5	6	120	600	"
4	16.5	6	120	600	"
5	16.5	6	120	600	"
6	16.5	6	120	600	"
7	16.5	6	120	600	"
8	16.5	6	120	600	"
9	16.5	6	120	600	"
10	16.5	6	120	600	"

4.1.1b Beam2

Loading condition: No Load, Boundary condition: Both ends free, Length of Beam: 410mm
Width of beam: 45mm, Dia of Thermal SMA: 0.5mm

Sl. No.	Current (Amp)	Deflection Y (mm)	Heating Time (sec)	Cooling Time (sec)	Remarks
1	4.5	2	120	600	While cooling it came back 11mm down from original position
2	4.5	7	120	600	Original position
3	4.5	7	120	600	2mm down from original poisition
4	4.5	8	120	600	Original position
5	4.5	7.5	120	600	Original position
6	4.5	7.5	120	600	Original position
7	4.5	7.5	120	600	Original position
8	4.5	7	120	600	1mm down from original position
9	4.5	7	120	600	Original position
10	4.5	7	120	600	Original position

5. RESULTS AND DISCUSSIONS

Beam1 and beam2 were fabricated by two different methods. Beam1 contains both thermal SMA as well as superelastic SMA and is initially flat. Whereas beam2 contains only thermal SMA, and not superelastic SMA, is initially curved. Since the diameter of thermal SMA wires used in beam2 is 0.5mm it was tested only at no load condition with the boundary condition of both ends free. Whereas beam1, which contains 1.2mm diameter thermal SMA wires, was tested with a uniformly distributed load of 0.5Kg.The results are explained as follows.

5.1 Beam1

Here the beam showed mid span deflection of 4.5mm initially and later stabilized value of 6.0mm was shown under a load of 0.5Kg which was uniformly distributed with a boundary condition of one end fixed and other end sliding as shown in fig.9.

5.1 Beam2

Here the curved beam in deactivated position went to flat condition when actuated under a boundary condition of both ends free. It underwent a mid span deflection of 7mm when actuated.

6. CONCLUSION

- A novel method of embedding SMA wires in composite beams to obtain large deformations has been evolved.
- Since the thermal SMA elements were placed eccentric to the neutral axis an appropriate method of imparting the biasing force has been arrived at. These include using the super elastic element as a biasing member or the host structure as the biasing member.
- The twisting of the SMA embedded beams has been minimized by slitting during lay-up of the beam.
- It has been demonstrated that it is possible to obtain a curved beam from an initial flat beam and vice-versa (by energizing the embedded SMA elements).
- The beams are able to carry and lift (vertical deflection) external load when embedded SMA is activated (maximum pressure = 27.1 kg/m^2).
- The future work will include:
  a) Fine tuning the embedding of SMA in the FRP laminate (in terms of Configurations).
  b) Obtain repeatable and consistent shapes of the beam in both energized and de-energized states.

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